

Do Black Holes Destroy Information?*

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I review the information loss paradox that was first formulated by Hawking, and discuss possible ways of resolving it. All proposed solutions have serious drawbacks. I conclude that the information loss paradox may well presage a revolution in fundamental physics.

Introduction. Over 15 years ago, Stephen Hawking proposed that the usual rules of quantum mechanics do not apply to a process in which a black hole forms and then completely evaporates[1]. If this proposal is correct, then we face the daunting task of finding a new conceptual basis for all of physics. Since Hawking's original work, this issue has been much debated, but it has not been definitively resolved.

When I began thinking seriously about black holes a few years ago, I was inclined to dismiss Hawking's proposal as an unwarranted extrapolation from an untrustworthy approximation. It seemed to be based on the premise that no (or hardly any) information about the body that collapsed to form the black hole can be extracted from the thermal radiation that the black hole emits. As best I could tell, this premise was founded on the semiclassical calculation of Hawking radiation[2], in which all gravitational back-reaction effects are neglected. Rather than accept Hawking's remarkable (and radical) suggestion, it seemed to me much more sensible (and conservative) to assume the validity of quantum mechanics, and to try to understand the mechanism by which information about the collapsing body gets encoded in the outgoing radiation.¹ I was hopeful that a detailed analysis of back reaction would reveal this mechanism. But I also expected that the mechanism would be sufficiently subtle and enlightening as to notably deepen our understanding of fundamental physics. I was especially hopeful that light would be shed on the meaning of the intrinsic black hole entropy.

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¹ The greatest champions of this viewpoint have been Page[3] and 't Hooft[4,5].

As I have pondered this puzzle, it has come to seem less and less likely to me that the accepted principles of quantum mechanics and relativity can be reconciled with the phenomenon of black hole evaporation. In other words, I have come to believe more and more (only 15 years behind Hawking) that the accepted principles lead to a truly paradoxical conclusion, which means that these principles cannot provide a correct description of nature. This may be analogous to the conclusion, derivable from classical physics, that the energy spectrum of black body radiation diverges at short wavelengths. Conceivably, the puzzle of black hole evaporation portends a scientific revolution as sweeping as that that led to the formulation of quantum theory in the early 20th century. Surely, this would be the most exciting possible outcome of the puzzle.

If the currently accepted version of quantum theory really is fatally flawed, then we must face the challenge of finding a new, self-consistent, formulation of the fundamental laws that agrees with experiment. So far, this task has attracted surprisingly little attention. Perhaps the time has come to intensify the search.

The Paradox. Hawking's discovery of black hole radiance established a deep and satisfying connection between gravitation, quantum theory, and thermodynamics. Particularly beautiful is the formula that Hawking[6] derived (and Bekenstein[7] anticipated) for the intrinsic black hole entropy

$$S = \frac{1}{4} A , \tag{1}$$

where A is the area of the event horizon in Planck units. This elegant result relegates the area theorem[8] of classical general relativity to a special case of the second law of thermodynamics.

At the same time, black hole radiance raises some serious puzzles. One puzzle concerns the interpretation of black hole entropy. In other contexts, statistical-mechanical entropy counts the number of *accessible* microstates that a system can occupy, where all states are presumed to occur with equal probability. If a black hole has no (or very little) hair, the nature of these microstates is obscure. Eq. (1) invites us to construe the horizon as a quantum membrane with about one degree of freedom per Planck unit of area[5], but a more concrete conception of these degrees of freedom remains elusive.

More distressing is a serious paradox raised by Hawking[1]. In his semiclassical calculation of black hole radiance, Hawking had found that the emitted radiation is *exactly* thermal. In particular, the detailed form of the radiation does not depend on the detailed structure of the body that collapsed to form the black hole. This is because the state of

the radiation is determined only by the geometry of the black hole *outside* the horizon, and the black hole has no hair that records any detailed information about the collapsing body. (While the semiclassical approximation used by Hawking is not exact, it is quite plausible that the emitted radiation really is only weakly correlated with the state of the collapsing body. The key constraint comes from causality—once the collapsing body is behind the horizon, it is incapable of influencing the radiation.²)

That the radiation outside the black hole is in a mixed (thermal) state is in itself neither surprising nor disturbing. After all, the region outside the horizon is only part of a quantum system, and there are correlations between degrees of freedom (quantum fields) that are accessible outside the horizon, and the inaccessible degrees of freedom that are behind the horizon. It is because of these correlations that the radiation detected by observers outside the horizon is in a mixed state.

But suppose that the black hole continues to evaporate until it disappears completely. Now the radiation *is* the whole system. And so it seems that an initially pure quantum state, by collapsing to a black hole and then evaporating completely, has evolved to a mixed state. In other words, even if the initial quantum state were precisely known, we cannot predict with certainty what the final quantum state will be; we can only assign probabilities to various alternatives. This is the information loss paradox. The paradox is that if we try to analyze the evolution of a black hole using the usual principles of relativity and quantum theory, we are led to a contradiction, for these principles forbid the evolution of a pure state to a mixed state. It is a familiar fact of life that information is often lost *in practice*.³ Here something essentially different is being claimed, that information is actually destroyed *in principle*.

Information regained? Hawking concludes that the usual rules of quantum mechanics cannot apply in all situations, which means that the fundamental laws of physics must be reformulated. Is there really no way to avoid this extraordinary conclusion? Let us examine some of the alternatives.⁴

1. Can the information come out with the Hawking radiation?

² See, for example, [9].

³ For a recent review, see [10].

⁴ For other recent discussions, see [11] and [12].

To a pragmatic physicist, the most likely place for the information to be hiding is in the Hawking radiation emitted by the black hole. After all, if we throw a volume of the encyclopedia into the sun, then for all practical purposes, information is destroyed. But we don't really believe that the information about the initial quantum state has been lost in principle. Even as the encyclopedia burns beyond recognition, all of the information that it carried presumably becomes stored in subtle and intricate correlations among the radiation quanta emitted by the sun, or correlations of the emitted quanta with the internal state of the sun. Information is lost in practice because we are unable to keep track of all these correlations.

Now suppose that we try to read the encyclopedia by measuring the sunlight. Even if we measure the properties of the emitted radiation to arbitrary accuracy, not much information comes out at first. The radiation is in a nearly thermal mixed state because it has complicated correlations with the internal state of the sun (which we are not measuring). But if we wait long enough for the "sun" to settle down to its unique quantum ground state, and stop radiating, then only correlations among the emitted quanta can carry information. There are certainly plenty of ways to encode information in correlations among quanta emitted by the system at different times. If we measure those correlations to sufficient accuracy (and we know the precise initial quantum state of the sun, before we threw in the encyclopedia), we can recover the encyclopedia.

So why should a black hole be fundamentally different? The pragmatic viewpoint holds that, in a similar way, the Hawking radiation emitted by a black hole seems at first to be in a mixed state[3]. But by the time the black hole has radiated away most of its mass, there are detailed and subtle correlations between the quanta emitted early and the quanta emitted later on. These correlations, in principle, carry all of the information about the quantum state of the initial collapsing body.

Since a black hole has no (or little) hair, the pragmatic viewpoint challenges us to explain how the black hole manages to record the information about the quanta that it has already emitted, so that it is able to induce these correlations. But there is a sharper way (impressed on me by Lenny Susskind) of expressing why the pragmatic view is implausible, and difficult to reconcile with causality[13,14]. On the spacetime of an evaporating black hole, it is possible to draw a single spacelike slice that crosses most of the outgoing Hawking radiation, and *also* crosses the collapsing body, well inside the (apparent) horizon. (We can also choose this slice to stay far from the singularity, in regions of low curvature, so we are confident that we know the causal structure reliably.)

Now, we know that if the outgoing radiation by itself is in a nearly pure state, it must *not* be strongly correlated with the state of the body inside the horizon. The trouble arises because, if the quantum state outside the horizon is really uncorrelated with the state inside the horizon, then it follows from the principle of superposition that the state inside the horizon must be a unique state that carries no information at all. The argument goes like this: Let $\{|i\rangle\}$ denote a basis for the initial quantum state of the collapsing body, and take the extreme view that each of these states evolves to a state on the spacelike slice constructed above, such that the radiation and the collapsing body are *completely* uncorrelated; we have

$$|i\rangle \longrightarrow |i\rangle_{\text{inside}} \otimes |i\rangle_{\text{outside}} \quad (2)$$

—the final state is the tensor product of a pure state inside the horizon and a pure state outside. But we may also consider a superposition of these basis states, which evolves as

$$\sum_i c_i |i\rangle \longrightarrow \sum_i c_i (|i\rangle_{\text{inside}} \otimes |i\rangle_{\text{outside}}). \quad (3)$$

In general, the state inside and outside will be correlated, *unless* all of the states $|i\rangle_{\text{inside}}$ are actually the *same* state. So the radiation will always be in a pure state only if the body is in a *unique* state. (This is reminiscent of how the “sun” settled down to its unique ground state in the example cited above.) More generally, if the radiation state is nearly pure, then the body’s state must be nearly unique. We conclude that, if the information really propagates out encoded in the Hawking radiation, then there must be a mechanism that strips away (nearly) all information about the collapsing body as the body falls through the apparent horizon (and long before the body reaches the singularity). In the lively imagery of Susskind[13], a mysterious force must bleach the encyclopedia as it tumbles into the black hole, removing the message that it contains. It is hard to imagine any reasonable way to achieve this, because to a freely falling observer the apparent horizon is not a very special place.

If bleaching of the information at the horizon does not occur, then macroscopic violation of causality seems to be required to transport the information from the collapsing body to the outgoing radiation. At the very least, the semiclassical picture of the causal structure must be highly misleading.

2. *Can the information be retained by a stable black hole remnant?*

The pragmatic view is that small corrections to the leading semiclassical theory build up over time, so that by the time the black hole has radiated away most of its mass, most of the information has been recovered. An advantage of this scenario is that we can hope to understand and analyze it without invoking Planck-scale physics. Most other proposed ways of escaping information loss are based on speculations about how a Planck-mass black hole behaves.

If semiclassical theory is not misleading, then the Hawking radiation emitted by a large black hole reveals little information about the collapsing body. If information is not lost, this must mean that the information is retained inside the black hole. When the black hole has evaporated down to the Planck size, the standard semiclassical theory of black hole evaporation is surely no longer applicable, as spacetime is subject to violent quantum fluctuations on this scale. We can not be sure what happens next without a deeper understanding of quantum gravity.

Perhaps quantum gravity effects halt the evaporation process, so that a stable black hole remnant is left behind. At first sight, this seems to resolve the information loss paradox, because all of the information about the initial collapsing object can in principle reside in the remnant. But upon further reflection, the cure may be worse than the disease. Since the initial black hole could have been arbitrarily massive, the remnant must be capable of carrying an arbitrarily large amount of information (about M^2/M_{Planck}^2 bits, if the initial mass was M). This means that there must be an infinite number of species of stable remnant, all with mass comparable to M_{Planck} .

It seems hard to reconcile this sort of infinite degeneracy with the fundamentals of quantum field theory, that is, with analyticity (causality) and unitarity[4]. The coupling of the remnants to hard quanta might be suppressed by form factors, but the coupling to soft quanta (wavelength $\gg L_{\text{Planck}}$) should be well-described by an effective field theory in which the remnant is regarded as a pointlike object. Then the coupling to soft gravitons, say, should be determined only by the mass of the remnant, and should be independent of its internal structure, including its information content. We should be able to use this effective field theory to analyze, for example, the emission of Planck-size remnants in the evaporation of a large black hole. For each species, the emission is suppressed by a tiny Boltzman factor $\exp(-\beta_{\text{Hawking}} M_{\text{remnant}})$. But if there are an infinite number of species, the luminosity is nonetheless infinite.

The emission of Planck-size remnants in the evaporation of a large black hole is merely an example of a soft process in which heavy particles can be produced, a process

that is expected to admit an effective field theory description. If such processes really have infinite rates (as would be expected if there are an infinite number of Planck-mass species), then these infinities will inevitably infect other calculated processes, as a consequence of unitarity. These infinities would be quite malevolent—they would destroy the consistency of the theory.

So if stable remnants are really the answer, an effective field theory description of the coupling of the remnants to soft quanta cannot be valid—the coupling must depend on the hidden information content of the remnant. Banks *et al.*[15] have recently offered a particularly vivid explanation of how this might be possible. In their picture, the information that resides in a black hole remnant is contained in a long, narrow throat that is attached onto spacetime. Production of remnants is heavily suppressed because it is necessary to add a large volume (the volume of the throat) to the background spacetime, and this process requires a large Euclidean action.

For a number of reasons, the arguments in [15] are not very convincing. The primary motivation underlying the suggestion that a black hole remnant has a long throat comes from studies of dilaton gravity, which arises as a low-energy limit of string theory. The extreme magnetically charged black holes in this theory[16,17] really do have infinitely long throats (if the length is measured by the “string metric” that determines how strings propagate on the background). But while the throat of the magnetically charged black hole is threaded with magnetic flux that prevents the throat from pinching off, it is unclear what would prevent the throat of an uncharged black hole from pinching off. If the pinch-off occurs, the information stored in the throat would be lost to a “baby universe” disconnected from our own universe (see (5.) below). Furthermore, the infinite volume that potentially allows the extreme hole to store vast quantities of information may be illusory. Dilaton gravity becomes strongly coupled far down the throat of the extreme black hole. The total throat volume in the weakly-coupled region is actually quite modest. Thus, to argue persuasively that a dilatonic black hole harbors a large amount of information, one must perform a nonperturbative analysis that currently seems intractable. Finally, especially since semiclassical methods are not really applicable, it is quite difficult to calculate production rates for the extreme holes, or to otherwise support the contention that the production rate is at odds with the effective field theory viewpoint.

Giddings[11] recently suggested a variation on the stable remnant idea, that a black hole that harbors a lot of information actually stops evaporating when it is still large compared to L_{Planck} . The more information, the larger the remnant. So the number of

species less than a specified mass M is always finite, and the contributions of remnants to soft processes can be heavily suppressed. It strikes me that this suggestion is at least as peculiar as the idea that effective field theory cannot be applied to the tiny remnants. The odd thing is that there must be arbitrarily large black holes that emit no Hawking radiation, contrary to semiclassical theory. This failure of semiclassical theory must occur even though the curvature at the horizon is arbitrarily small.

Another displeasing feature of the remnant idea (in either of the two forms above) is that it leaves us without a reasonable interpretation for the Hawking–Bekenstein entropy. If information is really encoded in the Hawking radiation, then it seems to make sense to say that $e^{S(M)}$ counts the number of accessible black hole internal states for a black hole of mass M . But if the information stays inside the black hole, then the number of internal states has nothing to do with the mass of the black hole. Indeed (if the remnants are Planck size), we can prepare a black hole of mass M that holds an arbitrarily large amount of information, by initially making a much larger hole, and then letting it evaporate for a long time. Thus, the number of possible internal states for a black hole of mass M must really be infinite. The beautiful edifice of black hole thermodynamics then seems like an inexplicable accident.

(If a black hole really destroys information, then the interpretation of the intrinsic entropy must be somewhat different, but perhaps still sensible. The black hole entropy measures the amount of *inaccessible* information. As the black hole evaporates, the entropy is transferred to the outgoing radiation. The entropy of the radiation does not result from coarse graining—the mixed density matrix characterizing the radiation is really an *exact* description of its state.)

Note that if we reject the idea of stable black hole remnants, there is a very important consequence—there can be no exact continuous global symmetries in nature.⁵ Suppose that Q is a putative conserved charge, and that $m > 0$ is the mass of the particle with the smallest mass-to-charge ratio. (We’ll take its charge to be one.) By assembling N particles, we can create a black hole with charge $Q = N$ and mass M of order Nm ; if N is large enough, we have $M \gg M_{\text{Planck}}$, so that semiclassical theory can be safely applied to this black hole. In fact, we can make M so large that the Hawking temperature is small

⁵ That the “baryon number” of a black hole is ill-defined was first emphasized by Wheeler[18] and Bekenstein[19]. That the complete evaporation of a black hole would transcend global conservation laws may have been first stressed by Zeldovich[20].

compared to the masses of all charged particles. Then the black hole will radiate away most of its mass in the form of light uncharged particles, without radiating away much of its charge. At this point, there is no way for the evaporation of the black hole to proceed to completion without violating conservation of Q ; there is no available decay channel with charge $Q = N$ and a sufficiently small mass. The only way to rescue the conservation law is for the black hole to stop evaporating, and settle down to a stable remnant that carries the conserved charge. Since this doesn't happen in semiclassical theory, it seems that we are forced either to Planck-size remnants, or the surprising breakdown of semiclassical theory for large black holes envisioned by Giddings. And there would be an infinite number of species, because N could take any value. If we accept the objections to the existence of an infinite number of remnant species, then, we must accept the consequence that the conservation law is violated.

This is an unusual kind of anomaly. There is a conservation law that is exact at the classical level, but is spoiled by quantum effects. Since the black hole “forgets” the value of the charge that it consumes, one may wonder whether loss of information is unavoidable in theories that suffer from this anomaly, theories in which the conservation law is violated “only” by processes involving black holes. I don't think that we are forced to this conclusion. It is at least a logical possibility that all of the information about the initial collapsing body is actually preserved as in (1.) above. That charge is not conserved (contrary to our initial expectation) need not imply that information is destroyed.

Note that this argument for nonconservation breaks down if there are massless particles that carry the conserved charge. It also does not apply (or at least, is not totally convincing) for *discrete* global symmetries—for example, a Z_n symmetry, where n is not too large.

3. *Can all of the information come out “at the end?”*

When I said that “the information comes out with the Hawking radiation” under (1.) above, I meant that, after most of the the mass of the black hole is radiated away, the state of the radiation that has been emitted is not really thermal, but is instead nearly pure. Another logical possibility is that the radiation remains truly thermal until much later (as the semiclassical theory indicates). Finally, when the black hole evaporates down to the Planck size, and semiclassical theory breaks down, information starts to leak out; it is encoded in correlations between the thermal quanta emitted earlier, and the quanta emitted “at the end.”

But if the black hole was initially very big, so that the amount of information is very large, then the information can not come out suddenly. The final stage of the evaporation process must take a very long time[21,22]. To get an idea how long it must take, we should count the number of quantum states that are available to the Planck-energy's worth of radiation that is emitted in the last stage. These quanta all have wavelengths that are much larger than the size of the evaporating object, so it is an excellent approximation to suppose that they all occupy the lowest partial wave. Thus, for the purpose of counting states, the problem reduces to a one-dimensional (radial) ideal gas.

Actually, the same is true to a reasonable approximation for a big black hole, since the emitted quanta have wavelength comparable to the size of the hole. As a warm up, let's consider the case of a big black hole first, and check that the Hawking–Bekenstein entropy counts the number of radiation states from which the black hole can be assembled. If the mass of the black hole is M , then the radiation state from which it formed must contain energy M inside a sphere with radius comparable to the Hawking evaporation time $t_{\text{Hawking}} \sim M^3$. (I am now using units with $M_{\text{Planck}} = 1$). The entropy S of a one-dimensional ideal gas with energy E and “volume” L is, in order of magnitude,

$$S^2 \sim EL . \tag{4}$$

So for $E \sim M$ and $L \sim M^3$, we find $S \sim M^2$, the Hawking–Bekenstein entropy.

(By the way, it is interesting to ask how the above analysis is modified if there are ν different species of massless radiation, with $\nu \gg 1$. Then the entropy scales like $S^2 \sim \nu EL$, but the Hawking time decreases like $L \sim M^3/\nu$. So we see that ν drops out of the entropy[6,23], and we can begin to understand how the black hole entropy can be a universal quantity, independent of the details of the matter Lagrangian.)

Now let's ask what the volume of a one-dimensional ideal gas would have to be, if the gas has the same entropy as above, but energy $E \sim 1$. Or in other words, how much would the gas have to expand adiabatically to cool down to $E \sim 1$. Evidently, it would need to expand by the factor M , so that $L \sim M^4$. If it takes a time t_{remnant} before the long-lived remnant finally disappears, then the radiation emitted during this time occupies a sphere of radius $L \sim t_{\text{remnant}}$; we thus obtain an upper bound[22]

$$t_{\text{remnant}} \gtrsim M^4 . \tag{5}$$

This bound is saturated if the final radiation is equilibrated—that is, if it is able to occupy nearly all of the states that are available in the allotted time. Of course, the decay of the remnant might actually take much longer, but it has to take at least this long.

Another way to say what is going on is that the remnant must emit about $S \sim M^2$ quanta to reinstate the information. Since the total energy is of order one, a typical quantum has energy M^{-2} and wavelength M^2 . Further, to carry the required information, these quanta must be only weakly correlated with one another. This means, roughly speaking, that they must come out one at a time, as non-overlapping wave packets. Since the time for the emission of each quantum is M^2 , and there are M^2 quanta, the total time is M^4 .

If the information comes out at the end, then, the scenario is that a black hole with initial mass M evaporates down to Planck size in time M^3 , but the time for the Planck-size remnant to disappear is much longer (at least M^4 .) The trouble is that, since M can be arbitrarily large, there must be Planck-size black hole remnants that are arbitrarily long lived, even if no species is absolutely stable. If there are an infinite number of species with mass of order the Planck mass, all with lifetime greater than googolplex, then we have all the same problems as if the remnants were absolutely stable.

For the sake of logical completeness, I'll note a variation on the Giddings[11] idea about massive remnants—namely massive metastable remnants. Perhaps the evaporation of a black hole that harbors a great deal of information departs significantly from semiclassical theory while the hole is still large compared to Planck size, and it starts to emit quanta that have wavelength much longer than the naive thermal wavelength. The more information, the larger the black hole when this starts to happen. Then we would have an infinite number of long-lived species, but only a finite number with mass below a given energy, which might be acceptable. But, we again would face the challenge of understanding how semiclassical theory can fail so badly for very large black holes.

4. Can the information be encoded in “quantum hair?”

An important ingredient in the information loss puzzle comes from the black hole uniqueness theorems of classical general relativity. It is because the geometry outside the horizon is insensitive to the detailed properties of the collapsing body that the Hawking radiation is uncorrelated with the state of the collapsing body, in the leading semiclassical theory. As we have noted, one who holds the position that information is encoded in the Hawking radiation is challenged to explain how corrections to semiclassical theory enable

the black hole to store an accurate record of how it was formed and what it has already radiated.

The main conceptual point concerning “quantum hair” on black holes[24,25] is that there are additional possibilities for hair that are missed in the analysis of black hole solutions of the classical field equations. This enables the black hole to record more information than we would naively expect, information that influences the Hawking radiation in a calculable way[26]. The moral is that the “no-hair principle” has limitations, and we should be cautious about drawing sweeping conclusions from it.

On the other hand, the discovery of quantum hair seems at first sight to offer us little guidance concerning the information loss problem. The type of quantum hair that has been analyzed in detail is associated with charges that can be detected by means of the Aharonov–Bohm effect. Such quantum numbers arise only in theories with special matter content. Furthermore, even in theories that have many varieties of quantum hair, it is possible to make a black hole that doesn’t carry any, and in that case the Aharonov–Bohm effect doesn’t enable us to find out much about the internal state of the black hole.

The first objection above, that quantum hair arises only in theories with special matter content, is not so compelling. Indeed, a very exciting possibility is that the effort to avoid information loss will lead us to a very special class of theories, or even a unique one (perhaps superstring theory). Still, it is hard to imagine that quantum hair (of the Aharonov–Bohm type) can really resolve the paradox. It seems that the idea would have to be that there are an infinite number of exactly conserved charges (associated with an infinite number of *unbroken* gauge symmetries), so that measuring values of all the charges would suffice to uniquely specify the internal state of an arbitrarily large black hole. These conservation laws would have to be quite different than the conservation laws that we usually think about. For example, suppose I make a black hole by allowing N hydrogen atoms to collapse. If all the information about the initial state is to be encoded in quantum hair, then it seems that each possible state of the atoms must be in a distinct superselection sector! The values of the conserved quantities are not at all what I would expect if I tried adding together the charges of the individual atoms; they depend in a highly nonlocal way on how the atoms are patched together (in flagrant violation of cluster decomposition). The conservation laws put exceedingly powerful constraints on the evolution of the system, so powerful that it is hard to understand how they have escaped notice in our low-energy experiments. If quantum hair really enables a black hole

to retain vast amounts of information, the challenge is to explain how local quantum field theory seems to describe low-energy physics so well.

There is a claim[27] that string theory provides just the sort of nonlocal conservation laws that are required, in the form of “*W*-hair,” but I don’t understand this idea well enough to give a useful appraisal.

5. Can the information escape to a “baby universe?”

Perhaps the most satisfying “explanation” for the loss of information in black hole physics was offered by Dyson[28], Zeldovich[20], and Hawking[29,30]. Their picture, described in (rather misleading) classical language, is that quantum gravity effects prevent the collapsing body from producing a true singularity inside the black hole. Instead the collapse induces the nucleation of a closed “baby universe.” This new universe carries away the collapsing matter, and hence all detailed information about its quantum state. The baby universe is causally disconnected from our own, and so completely inaccessible to us; we have no hope of recovering the lost information. Yet there is a larger sense in which information is retained. The proper setting for quantum theory, in this picture, is a “multiverse” which encompasses the quantum-mechanical interactions of all of the universes that are causally disconnected at the classical level. To the “superobserver” who (unlike us) is capable of perceiving the state of the whole multiverse, no information is lost; it is merely transferred from one universe to another. In a more correct quantum-mechanical language, black holes produce correlations between the state of the parent universe and the state of the baby universe, and it is because of these correlations that both the parent and the baby are described as mixed quantum states.

Still, it provides us little solace that the superobserver can understand what is going on. We want to know how to describe physics in the universe that we have access to. In this regard, it is quite important to observe that, since the baby universe is closed, the energy that it carries away is precisely zero. Its energy (and momentum) being precisely known, its position in spacetime is completely undetermined. Thus, the baby universe wave function is really a global quantity in our universe, with no spacetime dependence. As Coleman[31] and Giddings and Strominger[32] emphasized (in a somewhat different context than black hole physics), this means the baby universe Hilbert space has a natural basis, such that different elements of the basis correspond to different superselection sectors from the perspective of our universe. In each superselection sector, the baby universe state is a unique pure quantum state, and it follows that our universe is also described by a pure

state. Mixed states arise only if we commit the unphysical act of superposing the different superselection sectors.

The baby universe idea, then, seems to lead us to the following picture[30]: When a pure state collapses to form a black hole, and then evaporates, it evolves to a pure state. This state is predictable in the sense that if we perform the experiment many times with the same initial state, we always get the same final state. But the result of the experiment might not be predictable from the fundamental laws of physics; it might depend on what superselection sector we happen to reside in. (The exception would be if there is a principle, a “big fix,” that picks out a unique sector.) There may be many, many phenomenological parameters that we need to measure before we can predict unambiguously how a black hole with initial mass M will evaporate, conceivably as many as $e^{S(M)}$.

Not only is this conclusion disheartening, but we are still left without a satisfactory resolution of the information loss puzzle. Once we have measured all of the relevant parameters, and can make predictions, we still long to learn the *mechanism* by which the black hole remembers the initial state so that it knows how to evaporate. This leads us back to contemplate (1.)–(4.) above.

Outlook. The claim that black holes destroy information seems like a wild leap, until we examine the alternatives. All of the possibilities listed here seem to require rather drastic revision of cherished ideas about physics. Perhaps we are just being really stupid, and a crucial insight that has eluded us will allow everything to fall into place. But it seems increasingly likely to me that it is as hopeless to reconcile relativistic quantum mechanics with black hole evaporation as it would have been to understand the spectrum of black body radiation using classical physics. The information loss paradox may be a genuine failing of 20th century physics, and a signal that we must recast the foundations of our discipline.

The case against the self-consistency of relativistic quantum theory is not yet airtight. We can hope to make the case stronger, even without achieving a much deeper understanding of quantum gravity at short distances. In some respects, the hypothesis of an infinite variety of stable (or very long-lived) black hole remnants may be the most conservative proposed way of avoiding information loss. The arguments against remnants can be sharpened and generalized, or perhaps promising loopholes will be found.

The hypothesis that information is encoded in the outgoing Hawking radiation can also be fruitfully investigated. As noted above, it should be possible to address the issue without

considering the intricacies of quantum field theory at large spacetime curvature. Nor is it necessary to consider so complex a process as the gravitational collapse of many quanta to form a macroscopic black hole. Instead, the question of information loss can be probed by studying scattering of a single quantum off of an extreme black hole[33]. Extreme black holes emit no Hawking radiation, and in suitable models are absolutely stable objects. If quantum coherence is maintained, then the scattering should be described by an S -matrix. But if black holes destroy information, then no S -matrix should exist. Furthermore, an extreme black hole with a large charge is a big object, so that the scattering process does not seem to involve very-short-distance physics.

In a seminal paper, Callan, Giddings, Harvey, and Strominger[34] pioneered the analysis of scattering off of an extreme black hole in dilaton gravity, using a $(1+1)$ -dimensional semiclassical approximation that systematically includes gravitational back-reaction effects. (The dilaton is invoked so that one can plausibly argue that the quanta absorbed and emitted by the black hole are all in the S -wave; thus, a truncation to an effective $(1+1)$ -dimensional field theory is reasonable.) Their work stimulated much subsequent investigation over the past few months, which has been reviewed in [12]. The analysis of this system turns out to be more involved than initially envisioned, and cannot be completely carried out within the domain of validity of semiclassical methods. Still, further progress is likely to be achieved, and to provide new insights. A sufficiently thorough analysis might convincingly demonstrate that information is really lost during the scattering process.

If we conclude that quantum mechanics must be overturned, how are we to proceed? Hawking[1,35] suggested a new dynamics that specifies the evolution of a density matrix, rather than a wave function. His proposal was sharply, and cogently, criticized by Banks, Peskin, and Susskind[36]. They emphasized the difficulty of reconciling loss of quantum coherence with other principles, such as locality and conservation of energy. Very loosely speaking, loss of coherence can be modeled by coupling a quantum system to a source of random noise. But noise tends to heat a system up. If fluctuations at the Planck scale destroy coherence very efficiently, then the Planck-scale “noise” ought to produce a lot of quanta at the Planck frequency. This doesn’t seem to happen, nor could such a failure of energy conservation be easily accommodated in general relativity.

Part of the challenge before us is to find a “phenomenological” description of information loss. We need a generalization of quantum field theory, one that preserves the

successful low-energy predictions, yet can accommodate loss of coherence (or acausal propagation) at some level.⁶ Theories of this type might be very restricted in form. Banks *et al.*[36] took the pioneering steps toward demonstrating this.⁷

One's devout wish is that experiment can guide us, as it guided Planck and his followers. Perhaps unexpected clues about the new physics will be uncovered, or already have been without being recognized. Meanwhile, it is not so unrealistic to hope to make real progress via pure thought. Anyway, we don't have much choice.

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⁶ Phenomenological limits on loss of information are discussed in [37,38]. Some issues of principle are addressed in [9,39].

⁷ For a more recent discussion, see [40].

References

- [1] S. W. Hawking, *Phys. Rev.* **D14** (1976) 2460.
- [2] S. W. Hawking, *Comm. Math. Phys.* **43** (1975) 199.
- [3] D. N. Page, *Phys. Rev. Lett.* **44** (1980) 301.
- [4] G. 't Hooft, *Nucl. Phys.* **B256** (1985) 727.
- [5] G. 't Hooft, *Nucl. Phys.* **B335** (1990) 138, and references therein.
- [6] S. W. Hawking, *Phys. Rev.* **D13** (1976) 191.
- [7] J. D. Bekenstein, *Phys. Rev.* **D7** (1973) 2333; **D9** (1974) 3292.
- [8] S. W. Hawking, *Comm. Math. Phys.* **25** (1972) 152.
- [9] R. Wald, “Black Holes, Thermodynamics, and Time Reversibility,” in *Quantum Gravity 2*, ed. C. J. Isham, R. Penrose, and D. W. Sciama, Oxford (1981).
- [10] W. Zurek, *Phys. Today* **44** (1991) 36.
- [11] S. B. Giddings, *Phys. Rev.* **D46** (1992) 1347.
- [12] J. A. Harvey and A. Strominger, “Quantum Aspects of Black Holes,” Enrico Fermi Institute Preprint (1992).
- [13] L. Susskind, private communication.
- [14] L. Susskind and L. Thorlacius, “Hawking Radiation and Back Reaction,” Stanford Preprint SU-ITP-992-12 (1992).
- [15] T. Banks, A. Dabholkar, M. R. Douglas, and M. O’Loughlin, *Phys. Rev.* **D45** (1992) 3607; T. Banks and M. O’Loughlin, “Classical and Quantum Production of Cornuconions at Energies Below 10^{18} GeV,” Rutgers Preprint RU-92-14 (1992).
- [16] G. Gibbons and K. Maeda, *Nucl. Phys.* **B298** (1988) 741.
- [17] D. Garfinkle, G. Horowitz, and A. Strominger, *Phys. Rev.* **D43** (1991) 3140.
- [18] J. A. Wheeler, unpublished.
- [19] J. D. Bekenstein, *Phys. Rev.* **D5** (1972) 1239.
- [20] Ya. B. Zeldovich, *Sov. Phys. JETP* **45** (1977) 9 (*Zh. Eksp. Teor. Fiz.* **79** (1977) 18).
- [21] Y. Aharonov, A. Casher, and S. Nussinov, *Phys. Lett.* **B191** (1987) 51.
- [22] R. D. Carlitz and R. S. Willey, *Phys. Rev.* **D36** (1987) 2336.
- [23] W. H. Zurek and K. S. Thorne, *Phys. Rev. Lett.* **54** (1985) 2171.
- [24] M. J. Bowick, S. B. Giddings, J. A. Harvey, G. T. Horowitz, and A. Strominger, *Phys. Rev. Lett.* **61** (1988) 2823.
- [25] L. M. Krauss and F. Wilczek, *Phys. Rev. Lett.* **62** (1989) 1221.
- [26] S. Coleman, J. Preskill, and F. Wilczek, *Mod. Phys. Lett.* **A6** (1991) 1631; *Phys. Rev. Lett.* **67** (1991) 1975; *Nucl. Phys.* **B378** (1992) 175.
- [27] J. Ellis, N. E. Mavromatos, and D. V. Nanopoulos, *Phys. Lett.* **B267** (1991) 465; **B272** (1991) 261; **B284** (1992) 27, 43.
- [28] F. Dyson, Institute for Advanced Study Preprint (1976), unpublished.

- [29] S. W. Hawking, *Phys. Rev.* **D37** (1988) 904; S. W. Hawking and R. Laflamme, *Phys. Lett.* **B209** (1988) 39.
- [30] S. W. Hawking, *Mod. Phys. Lett.* **A5** (1990) 145, 453.
- [31] S. Coleman, *Nucl. Phys.* **B307** (1988) 867.
- [32] S. B. Giddings and A. Strominger, *Nucl. Phys.* **B307** (1988) 854.
- [33] J. Preskill, P. Schwarz, A. Shapere, S. Trivedi, and F. Wilczek, *Mod. Phys. Lett.* **A6** (1991) 2353.
- [34] C. G. Callan, S. B. Giddings, J. A. Harvey, and A. Strominger, *Phys. Rev.* **D45** (1992) 1005.
- [35] S. W. Hawking, *Comm. Math. Phys.* **87** (1983) 395.
- [36] T. Banks, M. E. Peskin, and L. Susskind, *Nucl. Phys.* **B244** (1984) 125.
- [37] J. Ellis, J. S. Hagelin, D. V. Nanopoulos, and M. Srednicki, *Nucl. Phys.* **B241** (1984) 381.
- [38] J. Ellis, N. E. Mavromatos, and D. V. Nanopoulos, “Testing Quantum Mechanics in the Neutral Kaon System,” CERN Preprint CERN-TH.6596/92 (1992).
- [39] R. Wald, *Phys. Rev.* **D21** (1980) 2742.
- [40] M. Srednicki, “Is Purity Eternal?” Santa Barbara Preprint UCSB-92-22 (1992).